TIME AND FREQUENCY ACTIVITIES AT NICT, JAPAN

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Abstract

At NICT, Japan, research and developments for the time and frequency standards are performed by the Space-Time Standards Group. The objectives of this group are to establish standards and reference of space and time as the fundamental basis for various fields of activities in science, engineering, and social activities, and to provide easy access to these foundations from wide range of communities. The recent activities and achievements of the group are reported in this paper.

1. INTRODUCTION

At National Institute of Information and Communications Technology (NICT) of Japan, research and developments related with time and frequency are currently conducted by the Space-Time Standards Group of the New Generation Network Research Center. The objectives of this group are to establish standards and reference of space and time as the fundamental basis for various fields of activities in science, engineering, and social activities, and to provide easy access to these foundations from wide range of communities. To carry out this concept, four research projects have been established in the group. The Japan Standard Time Project is responsible for the generation and maintenance of high-quality Japan Standard Time (JST) and UTC (NICT), as well as dissemination of them by various methods. The Atomic Frequency Standards Project is aiming to develop and operate primary frequency standard systems and optical frequency standard systems. In the Satellite Time Control Project, precise time and frequency transfer experiments between a ground-reference clock and an atomic clock on the satellite such as ETS-8 and the Quasi-Zenith Satellite System are being developed. The Space-Time Measurement Project is conducting research and development for precise time and frequency transfer and establishment of a spatial reference frame by using two-way satellite link methods, optical fiber transfer methods, and space geodetic techniques.

2. ATOMIC FREQUENCY STANDARDS

2.1. CESIUM PRIMARY FREQUENCY STANDARDS

The optically pumped cesium primary frequency standard (NICT-O1) stopped operation in June 2006. Instead of NICT-O1, the cesium atomic fountain primary frequency standard NICT-CsF1 is now in operation (Figure 1). It has been used for TAI determination by BIPM since 2006, and obtained international official recognition in September 2007 **[1]**. Its frequency uncertainty was reported in the Circular T No. 249 (October 2008) as 1.6×10^{-15}.

We have introduced a University of Western Australia built Cryogenic Sapphire Oscillator (CSO). Synthesis chains based on the CSO have been assembled without degradation of the frequency stability of the CSO. At present, the 1-GHz and 9.192-GHz signals, whose short-term stabilities are better than 2×10^{-15} at 1 s, are available as references for frequency standards **[2]**.

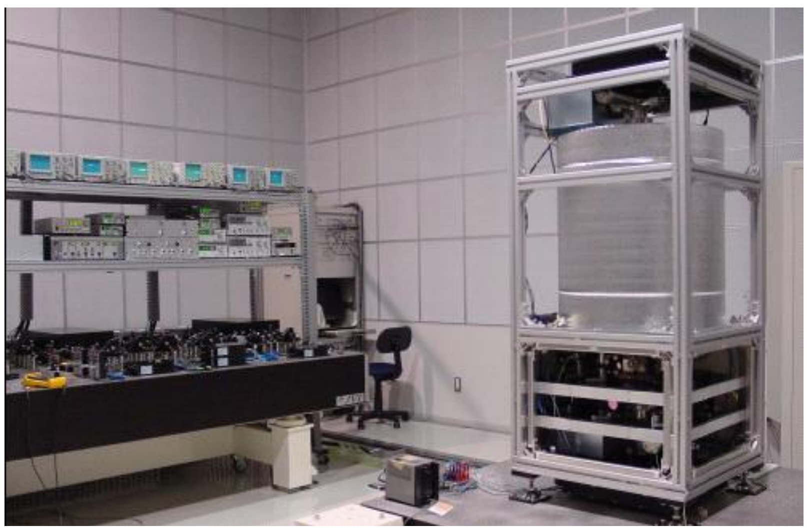

Figure 1. Cesium atomic fountain primary frequency standard (NICT-CsF1).

2.2. OPTICAL FREQUENCY STANDARDS

NICT is developing two kinds of optical frequency standards. One uses a single ion trap technique of $^{40}Ca^+$ (Figure 2). In June 2008, we reported the absolute frequency of clock transition of $^{40}Ca^+$ with an uncertainty level of 10^{-14} for the first time in the world **[3,4]**, whose value is in good agreement with the result given by the Innsbruck group **[5]**. At the 18th Meeting of the CCTF in June 2009, the $^2S_{1/2}$-$^2D_{5/2}$ transition of the $^{40}Ca^+$ was approved for inclusion in the list of recommended frequencies. The uncertainty of the frequency was adopted from the results reported by NICT, and the absolute frequency value was adopted from the weighted mean of the values reported by University of Innsbruck and NICT. Our present best estimate of the absolute frequency was obtained in August 2009 with the uncertainty of 1.2×10^{-14}.

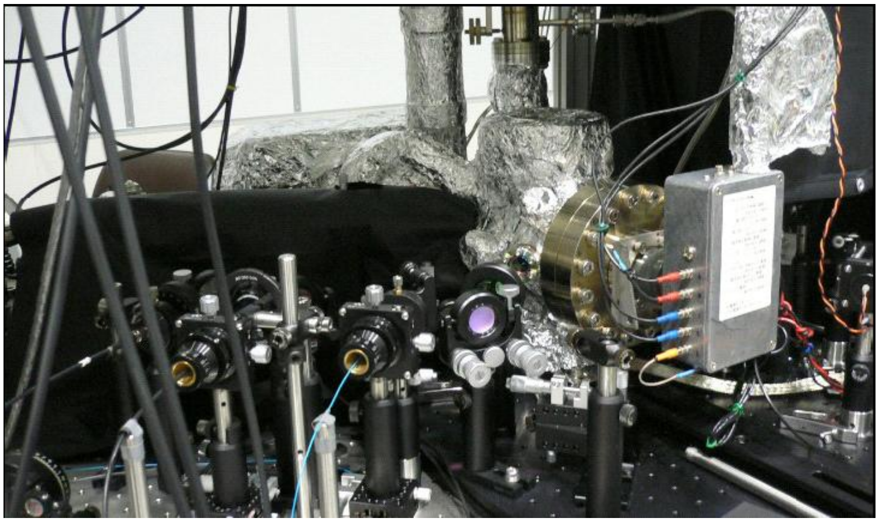

Figure 2. Optical frequency standard using an electric quadrupole transition in single, laser-cooled, trapped Ca^{+} ions.

The other is a Sr optical lattice clock (Figure 3). A two-stage magneto-optical trap of Sr atoms and the final trap by optical lattice potential have been successful. By using a preliminary stabilized clock laser system, the clock transition of ^{87}Sr atoms was observed with a linewidth of 1.2 kHz (FWHM) in October 2009. In theoretical research, the possibility of a new clock using a molecular transition has been suggested **[6,7]**.

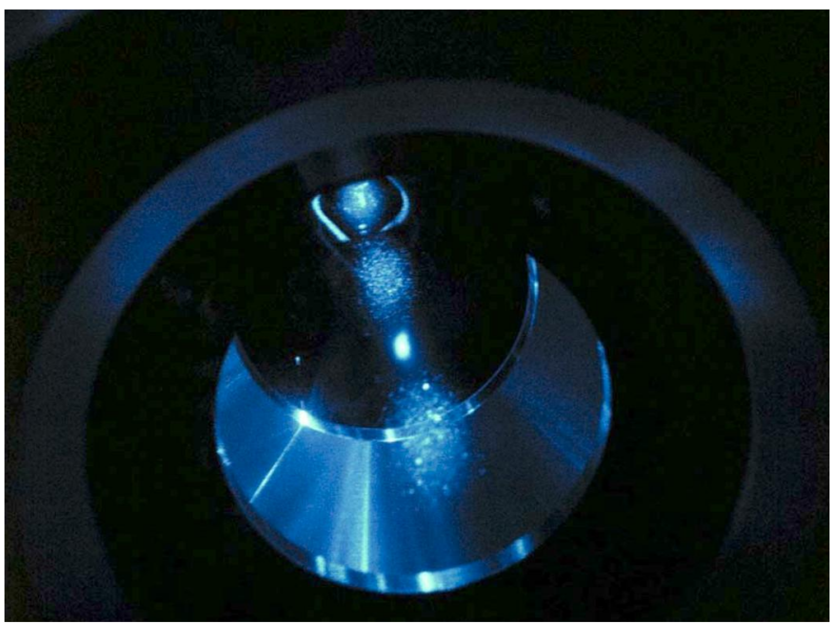

Figure 3. Emission of Sr atoms trapped by a laser cooling technique.

2.3. OPTICAL MEASUREMENT AND TRANSMISSION TECHNIQUE

Two optical frequency comb systems originally developed by using different lasers play an important role in the evaluation of optical frequency standards under development. Their frequency stabilities of 2×10^{-16} were confirmed by mutual comparison.

3. TIME KEEPING

UTC (NICT), the basis of Japan Standard Time, is a realization of an average timescale made by an ensemble of 18 Cs atomic clocks at NICT headquarters. We have four hydrogen masers and one of them is used as the source of the actual signal of UTC (NICT). The current generation system of Japan Standard Time started a regular operation in February 2006 and has worked well since then **[8]**. UTC (NICT) has been synchronized with UTC almost within ±20ns. Frequency stability of the timescale becomes better by improved timescale algorithm **[9]**. We are going to link the Cs ensemble timescale with NICT-CsF1 and make a self-reliant timescale TA (NICT).

4. PRECISE TIME AND FREQUENCY TRANSFER

4.1. GPS

NICT is collaborating with PTB to develop a portable frequency standard system composed of a passive hydrogen maser and a dual-frequency GPS receiver this year. PTB plans to use the GPS carrier-phase time transfer software developed by NICT for this system **[10]**. NICT and PTB performed GPS receiver calibration of both stations by using a NICT Septentrio receiver from September 2007 to June 2008. The P1/P2 bias of both receivers is within 1 ns with respect to a BIPM calibration result performed in April 2008.

A GPS software receiver based on a graphical processing unit has been developed. Our implementation is unique with its width of the correlation function so that simple data handling in the spectral domain become possible. Comparison with output from a commercial hardware receiver confirmed the consistency and accuracy of our development.

4.2. TWSTFT [11]

NICT and major T&F institutes in the Asia-Pacific region, such as NMIA in Australia, NTSC in China, TL in Taipei, Taiwan, and KRISS in Korea are cooperatively constructing a TWSTFT network in this region. Time transfer is regularly performed and data/hour are reported to the BIPM. NICT carried out calibration trips by using a portable station between NICT and KRISS in October 2006 and NICT and NMIJ in February 2007. We are planning to perform the calibration trips again, since the satellite has been changed from JCSAT-1B to IS-8 in 2009.

A TWSTFT link between NICT and PTB has been established by using IS-4 satellite. The time transfer is performed hourly and the data are also reported to the BIPM. The TWSTFT link between NICT and USNO via VDB relay station was closed November 2006 because the link quality was very low. We plan to restart the observations with a new relay station in Hawaii. NICT is developing a TWSTFT system using dual Pseudo Random Noise (PRN) and testing it with an actual satellite link.

4.3. FREQUENCY TRANSFER USING OPTICAL FIBER [12]

An optical fiber RF dissemination system equipped with an active phase-noise compensation function has been developed. A test experiment was successfully conducted on an urban telecom fiber link of length 114 km in Tokyo area. We have achieved a transfer stability level of 10^{-18} at an averaging time of 1 day (Figure 4). We also performed the RF transfer over 204 km in an urban fiber link by cascading two systems. It was verified that the transfer stability degrades by the factor $2^{1/2}$ in the two-stage cascaded system for the first time in the world.

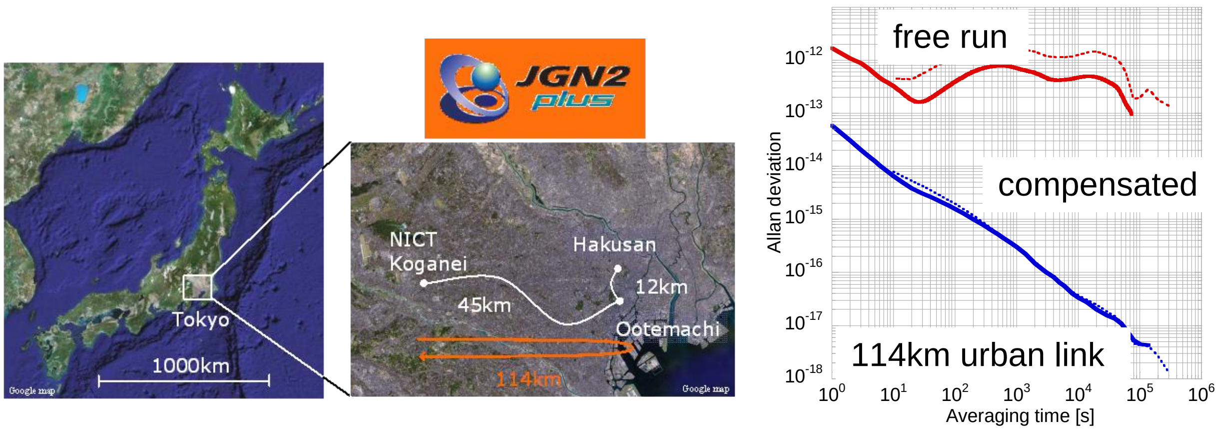

Figure 4. The fiber link used for the frequency transfer experiment and the achieved frequency stability.

As an application of ultra-stable frequency dissemination, a 1-GHz signal based on the CSO was transferred through a 25-km fiber and used as a microwave reference for an optical frequency comb. A fractional frequency stability of an ultra-narrow clock laser for a Ca-ion optical frequency standard was measured by the comb as 9×10^{-15} at 1 s, which included both the laser stability and transferred reference stability.

4.4. ETS-VIII

NICT is conducting a precise time and frequency transfer experiment between a ground-reference clock and an atomic clock on the satellite ETS-8 (Engineering Test Satellite -8). ETS-8, which was launched in late 2006, is a Japanese geostationary satellite equipped with cesium-beam frequency standards. NICT developed equipment to carry out two-way time transfer with the S-band by using both code and carrier-phase measurement. The precision of the code phase reaches 1 ns for a 1-second measurement and that of the carrier phase is of the order of 10^{-12} for 1 second, which is better than the traditional method by two orders **[13]**. The stability of the onboard atomic clock was evaluated in an averaging time of 1 second.

4.5. QZSS

Japan has started a project of Quasi-Zenith Satellite System (QZSS) since 2003 (Figure 5). QZSS will be highly useful as a supplement to the modernized GPS in urban canyons and mountainous areas with its high visibility brought out by its inclined orbits. In this project, NICT is developing a time management system **[14]**. By conducting two-way time transfer between the onboard clock and the clock at the ground station by using a Ku-band link, the management of the QZSS system time, which links to UTC (NICT), is expected to achieve nanosecond level. The proto-flight model (PFM) of the onboard equipment and the ground system has been developed. Three monitoring stations with TWSTFT and two time management stations are being built. The first satellite is planned to be launched in 2010.

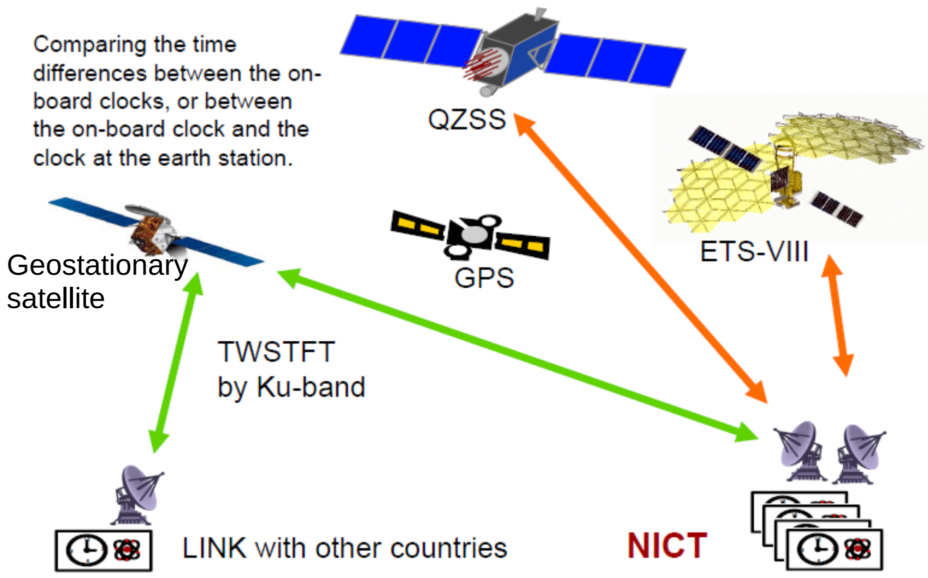

Figure 5. Time transfer systems at NICT.

4.6. VLBI

In the usual geodetic analysis using Very Long Baseline Interferometry (VLBI), clock offsets and their rates of change at each station are precisely estimated with respect to a selected reference station. The averaged formal error (1 sigma) of the clock offsets is typically about 20 picoseconds when analyzing geodetic VLBI experiments which are regularly conducted by the International VLBI Service for Geodesy and Astrometry (IVS). This precision is nearly one order better than other techniques like GPS or two-way satellite time transfer. We primarily evaluated the ability of VLBI frequency transfer by comparing it with GPS carrier-phase frequency transfer. We selected the two stations (Onsala, Wettzell) which belong to IVS and the International GNSS Service (IGS) network. These two stations have in common that at each site VLBI and GPS share the hydrogen maser. VLBI is more stable at averaging periods longer than 10^3 s, as shown in Figure 6. In addition, the VLBI frequency transfer stability follows a 1/tau law very closely when averaging up to 10^4 s, and it has reached about 2×10^{-11} s (20 ps) at 1 s.

In order to evaluate a capability of VLBI frequency transfer in more detail, we are carrying out geodetic VLBI experiments using the Kashima-Koganei baseline (about 110 km). GPS measurements are also simultaneously performed to compare with VLBI analysis. We plan to investigate the longer-term stability of VLBI frequency transfer up to 1 week based on the experiments. In addition, we are now developing a compact and transportable VLBI system for providing reference baseline lengths to validate surveying instruments such as GPS and EDM. We are going to assess whether the compact VLBI system is feasible or not for the purpose of precise frequency transfer.

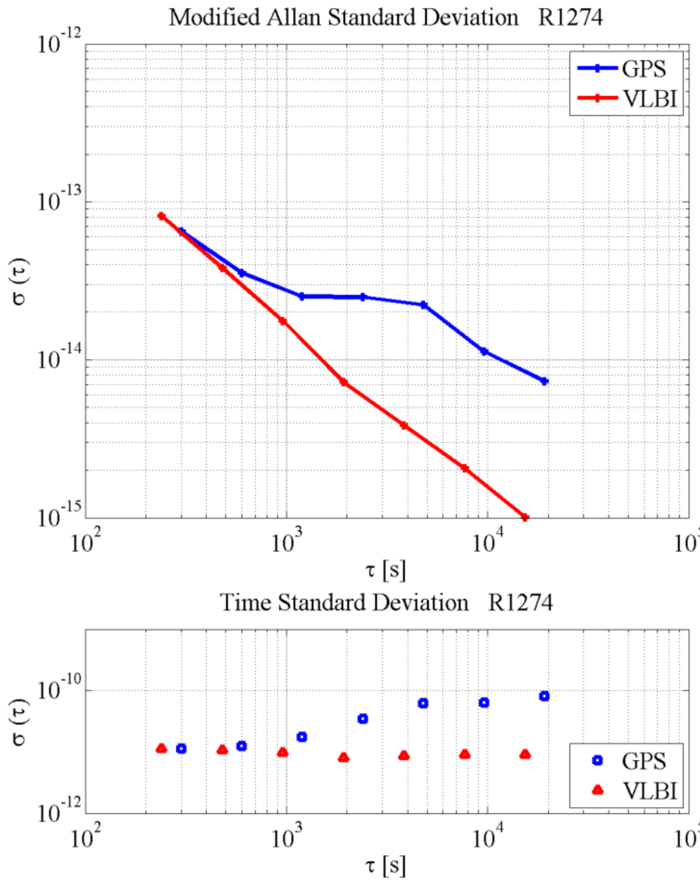

Figure 6. Modified Allan deviation (top) and Time standard deviation (bottom) of VLBI and GPS carrier phase results from an IVS session.

5. DISSEMINATION

5.1. STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

NICT provides the dissemination service of standard-frequency and time-signal via LF band, as shown in Figure 7. The signals from the two LF stations, namely Ohtakadoya-yama station and Hagane-yama station, cover whole Japan. Table 1 shows the characteristics of the stations. Both stations operate 24 hours a day. A market of radio-controlled watches and clocks has been developed.

5.2. FREQUENCY CALIBRATION SYSTEM FOR TRACEABILITY

NICT have been conducting a frequency calibration service referenced to UTC (NICT). In order to fulfill the requirements of global MRA, NICT have established a quality system for the frequency calibration service, which was assembled by the accreditation body, the National Institute of Technology and Evaluation. The conformity to ISO17025 was certified at the end of March 2001. The NITE (National Institute of Technology and Evaluation) provided an accreditation of ISO/IEC 17025 to NICT on 31 January 2003, and also provided an accreditation of ISO/IEC 17025 for the frequency remote calibration system to NICT on 2 May 2006; the BMC of the system is 5×10^{-14} since April 2007.

Table 1. Characteristics of LF stations.

	Ohtakadoya-yama	Hagane-yama
Frequency	40 kHz	60 kHz
E.I.R.P	13 kW	23 kW
Antenna	250 m height	200 m height
Latitude	37°22' N	33°28' N
Longitude	140°51' E	130°11' E

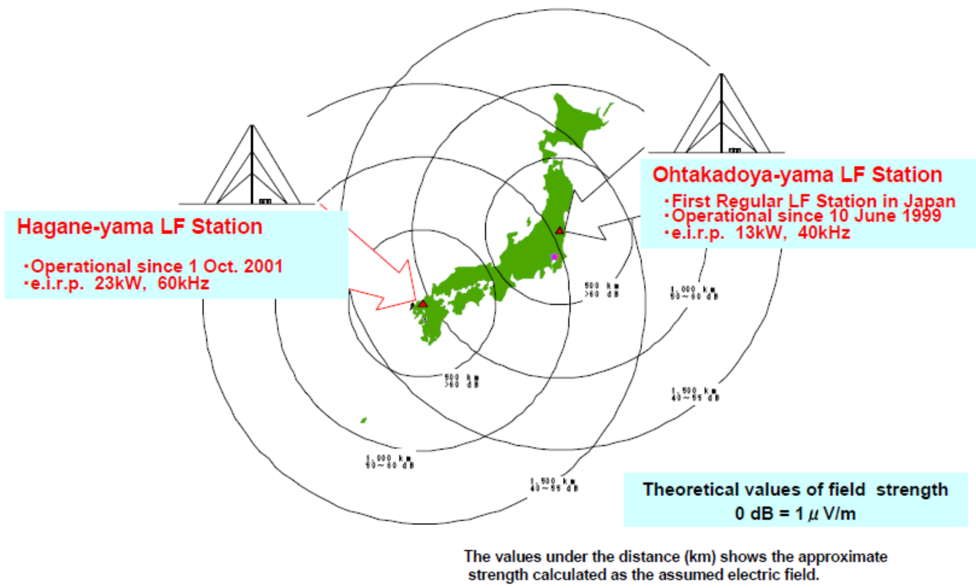

Figure 7. LF time and frequency service stations in Japan. The values under the distance (km) show the approximate strength calculated as the assumed electric field.

5.3. Public Network Time Protocol Service

NICT has been providing public Network Time Protocol (NTP) service since 2006 using a Field Programmable Gate Array (FPGA)-based NTP server which can accept NTP requests up to 1 million per second. We have also developed a stand-alone NTP server which consists of a Linux controller unit integrated with the FPGA and the NTP server hardware. The stand-alone NTP server started operation in 2008, and we are receiving about 100 million accesses per day on average.

6. Trusted Time Stamping

An accreditation program for time-stamping services in Japan started in February 2005. In this program, the clock of the time-stamping server is calibrated within the prescribed accuracy and traceability to UTC (NICT) for every time stamp issued. The accuracy of the clock of the time-stamping server is prescribed to be 1 second or better to UTC (NICT). NICT is the official time supplier for this accreditation program. A new draft recommendation about the methods to provide trusted time source for the time-stamp authorities was proposed to the Study Group 7 (Science Services) of the ITU-R in

September 2009, and it was approved with minor modifications. The new recommendation is now under the final approval procedure among the ITU-R member states.

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